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Recycling of spent lead/acid batteries: the case of Greece

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Abstract

In this study, the application of modern recycling technologies in accordance with the European and Greek legislation, aiming at the recovery of lead, polypropylene and sulfuric acid from spent lead (Pb)/acid batteries, is presented. The present state of their disposal and exploitation is also depicted. The international situation is reviewed, the general trends are marked and the main technologies related to lead/acid battery treatment are reported. General recommendations are given regarding the collection of spent batteries and the installation of a recycling plant in Greece. A sensitivity analysis is carried out in order to define the most significant parameters affecting the viability of a recycling scheme. The present study proves that a possible installation of a Pb/acid batteries recycling process unit, treating 17 000 t/year (estimated total quantity) and situated in the industrial area of the greater Athens region, seems to be economically profitable. The already existing operation of small-scale battery recycling plants, common in small countries, should be discouraged as they demonstrate a rather not environmentally acceptable recycling operation. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Environmental protection and conservation of natural resources have become a subject of great importance at national and international levels. The environmental issue in industrial countries throughout the world has been, and will continue to be, how to best manage hazardous waste. The issue has manifested itself in a multiple form: how to prevent environmental deterioration caused by the generation of hazardous wastes, how to effectively clean up the problem caused by passed examples of improper disposal, how to minimize the generation of hazardous wastes, and, finally, how to recover and recycle their contained valuable material by producing secondary material and conserving resources [1]. All these are complex issues depending, for resolution, on many social, technical and legislative factors. The disposal of batteries has become an ever-increasing topic of discussion in the past few years, due to the presence of heavy metals such as lead, mercury and cadmium.

The present study concerns the recycling of lead/acid batteries in Greece. The main scope is to estimate the feasibility of construction of a recycling plant, in order to reclaim the lead, the polypropylene and the sulfuric acid solution from automotive batteries. The aim is not to propose a technological innovation, but to use a method applied in other industrial countries and to evaluate the impact of national parameters to the financial optimal solution. The market survey and the study of the international know-how are based on bibliographical research of a web-site database and European and American patents. Our study is focused on the starting, lighting, and ignition (SLI) batteries, for the reason that the SLI batteries represent an amount equal to the 70–80% of the total quantity of lead/acid batteries in Greece.

2. The lead/acid battery

Since its discovery by Plante in 1859, the lead/acid battery has been undergoing a continuous evolution, both in the choice of its component material and in the nature of its design. Until the 1980s, the active part of the battery was contained in either a bakelite or an ebonite box. Today, it is generally housed within a polypropylene casing, which is able to resist very low temperatures, such as those in southern countries during summer conditions [2]. The lead/acid battery is a complex industrial product constituted by several materials. The main components of a lead/acid battery are [3]:

1. Active mass
 - Anode (negative electrode) consisting of PbO_2
 - Cathode (positive electrode) consisting of Pb
2. Metallic grids, metallic connections
3. Electrolyte (aqueous solution of H_2SO_4)
4. Polypropylene casing (box)
5. Other components (wood, paper, PVC)

By a redox reaction, chemical energy is converted to electrical energy, producing insoluble PbSO_4 from Pb and water. The size and shape of an SLI battery could be considered adequately stable (rectangular box, ~ 14 kg of weight). The composition of an average lead/acid battery is: 64% Pb, 5% polypropylene, 28.5% H_2SO_4 , 2.7% other materials [3].

3. Market survey for the lead

The use of lead/acid batteries is increasing in Greece, due to the increase of vehicles. An international market survey was conducted and its outcome showed the following.

- The problem of lead recovery from spent lead/acid batteries has received increasing attention in recent years. About 47% of the total world lead production results from lead secondary smelting [3] and about 80–85% of spent batteries are recycled [1]. The unreclaimed 15–20% of lead/acid automotive batteries is estimated to contribute approximately to the 65% of the total lead found in solid waste.
- The growth potential of Pb to the end of the century is around 3.5%. Nearly all primary lead production is based on sulfuric ores, which have proved global reserves in the order of 80 million t, which are expected to be exhausted within 30 years. The lack of considerable Pb resources resulted in the increase of its price [4].
- Almost all secondary metals consume far less energy due to the fact that most metallic scraps are very high-grade raw materials. The recycling of lead from spent batteries is not only a substitute for the shortage of Pb, but a Pb recovery at relatively low energy requirements; 36% of the requirement of primary lead production [4].
- The Pb recycling technology is well-established and can be simplified for a medium ($\sim 10\,000$ t) production, or it can incorporate automated handling system for large-scale ($\sim 30\,000$ t) capacities. [5].
- The profitability of plants of this capacity has been proven [5]. The secondary lead industry, coupled with production of batteries, needs less than 50% of the capital investment of the primary lead production [4].
- The wastes generated by the process can be either re-used or eliminated [5]
- The spent Pb/acid battery is a complex material, made of several different components (metal, plastic, liquid). Further recycling processing of polypropylene has been developed and enables the separation, reclamation and production of high-quality constituent materials that are suitable for use by the automotive industry at a price competitive with virgin materials.[2,3,5]
- The legislation concerning lead/acid batteries is both extensive and complex. European regulation has become more demanding and stricter. Increased focus on environmental issues by government bodies, environment groups and local communities will result in more compliance standards [6]. The European Economic Community (EEC) regulation requires that EEC states establish separate

lead/acid batteries collection, disposal and recycling program. In many European countries, individual actions have been promoting the collection of spent batteries. [7]

Consequently, the market condition of lead and the legislation established has necessitated the recycling of spent lead/acid batteries in Greece. A recycling scheme applied in Greece must have a form that secures the maximum flow of scrapped batteries to the lead recovering process and to respect environmental protection. This scheme could be a process unit in an existing Greek industry or in a new recycling plant. However, prior to the installation of a recycling plant, the collection of the scrap batteries must be assured. In Greece, the need for a collection scheme is not still defined. Decisive factors, which will influence the collection of the available scrap batteries in Greece, could be as follows.

- A recycling program, which will create a general consensus on the batteries disposal by the car owners, that means that a car owner shall dispose of a lead/acid battery only at a retailer, distributor, manufacturer or collection center.
- Creation of collection centers and incentives to encourage extensive recycling.
- The offered price for the used battery: It can influence the financial viability of the collection scheme and can motivate the delivery of scrapped batteries to the collection centers.
- Disposal and recycling opportunities should be located and contractually establishing the initial stages of developing a recycling program.
- The regulatory compliance status of all of the companies with recycling units in Greece should be investigated prior to the usage of a disposal facility, in order to ensure that there are no restrictions or environmental problems that could prevent batteries from being sent to these facilities.

The Pb price used for the calculation purposes of this study is 770\$/t for the year 1997 [8] and the offered price for the used battery is 222\$/t [8].

4. Recycling of spent lead/acid batteries

4.1. Estimation of the total amount of spent batteries in Greece

Prior to the estimation of the viability of a recycling scheme, one must have a realistic estimation of the total amount of spent batteries in Greece and the geographical distribution as well. In order to make this estimation, and since the collection system is not organized, we based our theory on the following.

- The total number of vehicles circulated in Greece (Fig. 1).
- The prediction concerning the increase of the number of vehicles in Greece and the typical recycling rates of lead/acid batteries in other European countries (4500–18 000 t/year) [5,9].
- The battery quantities that are imported annually (Fig. 2), as well as the quantities that are produced at the largest Greek battery industries.
- An opinion survey among people, who are involved directly or indirectly in car batteries (car mechanics, car dealers and owners), brought to surface that the life

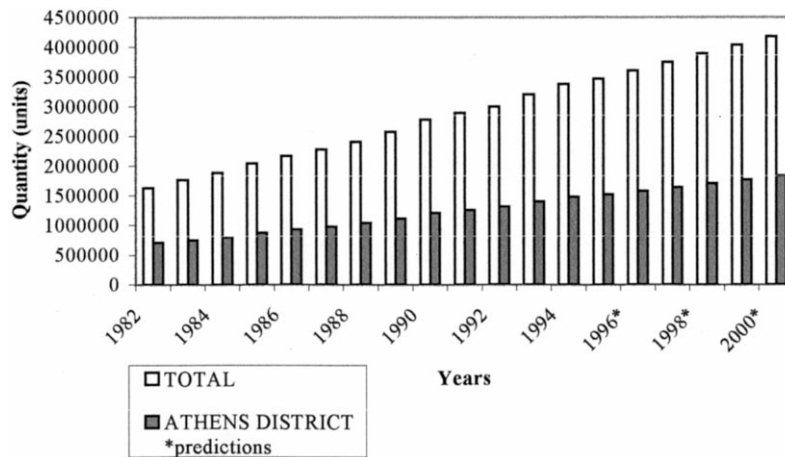


Fig. 1. Cars and motorcycles in Greece (1982–2000) [10].

expectancy of the battery is predicted to be 3.5–4.5 years, regardless of the distance covered by each specific vehicle.

Using the data retrieved by the National Statistic Service of Greece (Fig. 1), the quantity of vehicles is predicted to be 4 000 000 for the year 1998 and 4 200 000 for the year 2000. According to this prediction, the total number of spent batteries in Greece for the year 2000 is estimated to be 1 200 000, which equals 17 000 t/year. This result is in agreement with the predictions from the data presented in Fig. 2 ($\sim 1000\ 000$ battery/year for the year 1998), combined with the fact that the annual

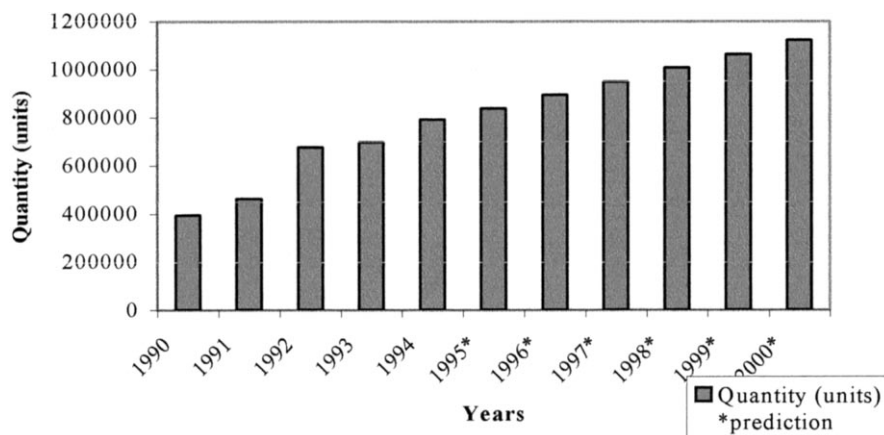


Fig. 2. Battery imports in Greece (1991–2000) [10].

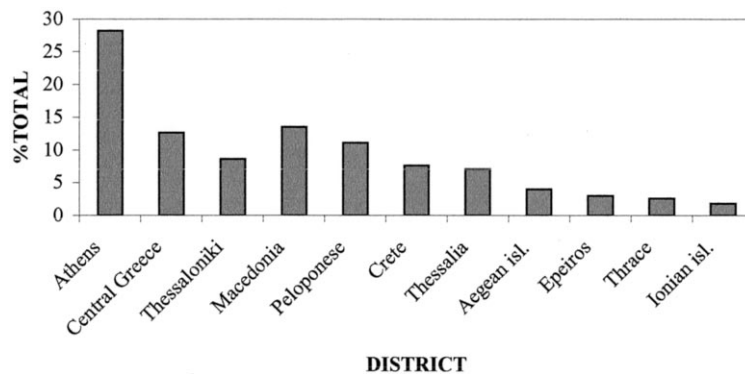


Fig. 3. The geographical distribution of batteries in Greece [10].

domestic production is approximately 100 000 battery/year [10]. The geographical distribution of batteries in Greece is given in Fig. 3. It indicates that the major part of the total amount is in the greater Athens region.

4.2. The collection scheme

The problem of lead/acid battery recycling in Greece is not yet considered totally, causing violations of the law and environmental problems, despite the legislative framework (73537/1438 and 19396/1546/1997), which is in harmonization with the EC's regulations (91/157 EC and 93/96 EC). According to the Greek legislative framework [11,12]:

- The disposal in surface or sewage water or land of liquid content of the lead/acid batteries is strictly restricted (article 4, paragraph 1.c).
- The establishment of technical rules referring to the transportation of the batteries to the recycling plants is encouraged (article 5, paragraph 1.c).

The existing alternatives for the collection of batteries in Greece are the following [8,13,14]:

- The car-owner discards the used battery after its replacement, most commonly without any separation from other types of refuse.
- The car-owner leaves the used battery at the car-service station, where it is replaced by a new one. All the used batteries are transported by private lorry-owners (collectors of metal or other recoverable materials) and directed to junk yards. There, they are crushed and deprived of their valuable lead content. The rest of the material is discarded.
- The battery follows the above-mentioned procedure up to the junk yard. After being crushed and emptied from the acid, they are transferred by private lorries to a recycling plant for further treatment.

Therefore, the elimination of uncontrolled refuse of batteries or parts of them after treatment and the decrease in the number of mediators between the car-owner and the recycling industry, is a main concern.

4.3. Existing recycling plants in Greece

Despite the fact that an organized collection system does not exist in Greece, there are three cases of lead/acid battery recycling sites, where 80% of the annual load of used lead/acid batteries is nowadays handled. This resulted from a market survey and a search we conducted around the Greek territory. The three existing recycling sites are:

- ALAKO (Lavrio—capacity of $\sim 250\,000$ battery/year).
- ATHIMARITIS (Aspropirgos—capacity of $\sim 200\,000$ battery/year).
- MAVROULIS-PYROVOLOS (Oinofita—capacity of $\sim 450\,000$ battery/year).

Apart from the three major sites involved with the lead/acid treatment, there is a plethora of small smelters all around Greece, which operate without conforming to the basic rules instituted by the law, against the uncontrolled polluting of air and ground.

The stages in the existing recycling sites are as follows [8].

- Battery braking and separation of its components.
- Smelting the grids and the active mass in a furnace under 1100°C , adding Fe, coke and silica compounds.
- Lead-refining in a kettle under $300\text{--}400^{\circ}\text{C}$, by adding NaOH, NaCl or NH_3NO_3 .
- Molding lead into ingots.

Taking into consideration the European experience [8,15] and the technology used in European plants, it is self-evident that the ‘primitive’ recycling sites in our country cause the following problems.

- The braking and the separation of the battery’s components in two out of the three above-mentioned industries, is carried out before the transportation of the batteries to the recycling plant. Therefore, the disposal of the acid is being done without the adequate steps of neutralization.
- All the quantities of FeSO_4 (estimated to be 14% of the feed, or 2500 t/year), which is the main by-product of the smelting process, are lost. This involves an environmental impact and reduction of profits from sales as well.
- The grids and the active mass are treated simultaneously. Therefore, there is a need for applying extremely high temperature (1100°C) demanded by the direct melt-reduction reaction of sulfate.
- The emissions of gases from the furnace contain a large amount of Pb particles (50 kg Pb/150 kg gas), which are emitted into the atmosphere. Considerable amounts of sulfur oxide and other malodorous or noxious compounds and dust are emitted to the atmosphere as well. Equipping the main unit with gas-emission abatement units would increase the investment and operating costs, considering the significant problems of corrosion and erosion related to the components of these gases.
- The process demands consumption of large amounts of reducing agents (Fe, coke, silica compounds) and desulfurization assistants (NaOH, NaCl, NH_3NO_3). Therefore, the operating costs are greatly increased.
- The complicated reaction mechanism delimits the total efficiency ($< 70\%$).

Considering the existing companies, one could notice that the applied technology is not in complete accordance with the legislative framework (paragraph 3.1). Noticeable are the attempts carried out by the Ministry of the Environment of Greece, focusing on public and state awareness of subjects related to battery recycling [13]. For the reasons reported, it seems to be a necessity for the improvement of the present situation of battery recycling in Greece, by applying effective methods of collection and by the modernization of the present technology, because there is a high risk in designing a spent battery recycling plant without securing adequate supplies and without taking into consideration the environmental impacts of the technology used.

In conclusion, the construction of a lead/acid batteries recycling plant needs, with the following priority, consideration of:

- prior to all, organization of a collection scheme to secure the supplies;
- use of modern technology securing environmental protection.

4.4. Recycling and utilization stages of spent batteries

The recycling technologies for the recovery of component materials from batteries are based on both hydrometallurgical and pyrometallurgical processes. The hydrometallurgical route is based on crushing the battery, followed by a physical separation of structural elements. In a second step, the major metals are separated by physical methods, liquid-liquid extraction, flotation and/or ion-exchange. Some of the chemicals are recovered as metal by electrochemical technologies. Most of the metals found in batteries are soluble in conventional leaching media (e.g. fluoroboric or fluorosilicic acid), from which they can be further recovered by salt precipitation or metal decomposition on cathodes of an electrolysis cell [16–18]. The second technique (pyrometallurgical) differs from the hydrometallurgical on the stage of the treatment of the battery paste, which is contacted by thermal means in a rotary furnace, in order to recover the contained lead [5,19,20]. Both processes require:

- significant power consumption (hydrometallurgical); long processing time (pyrometallurgical);
- expensive equipment (corrosive environment);

Table 1
Quantities of secondary products per ton of battery [21]

Product	Quantity (kg/t battery)
Metallic lead	550–600
Polypropylene	50
(Dry) Na ₂ SO ₄	60
15% sol. H ₂ SO ₄	300
15% sol. NaOH	300

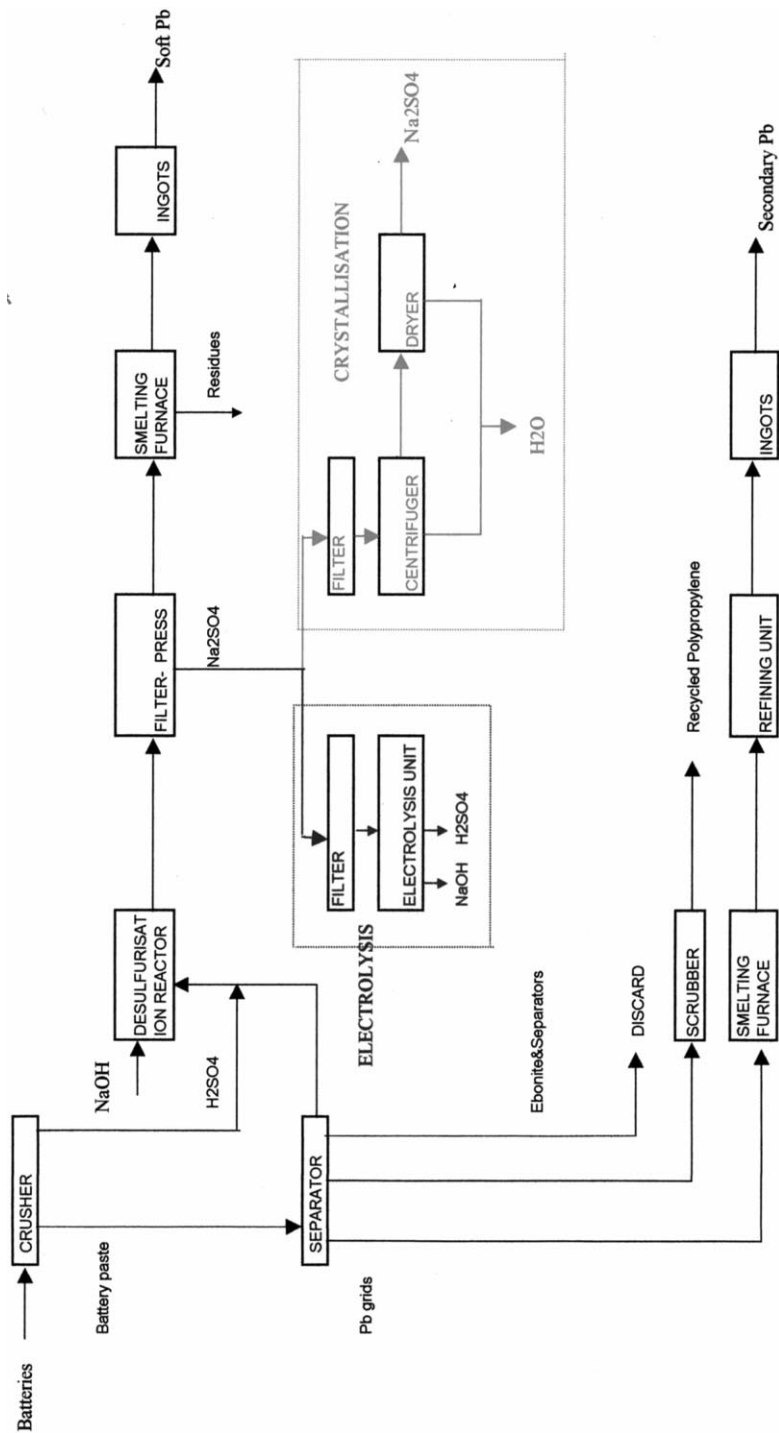


Fig. 4. Typical generalised flow diagram of the Pb/acid batteries recycling process, depicting the two major process alternatives.

Table 2

Results of the sensitivity analysis [22]

Case 1	Crystallization of Na_2SO_4
1. Capacity, (t/year)	15 000–17 000
2. Pb, price (\$/t)	755–776
3. Pb, yield (%)	58–60
Case 2	Electrolysis of Na_2SO_4
1. Capacity, (t/year)	11 000–17 000
2. Pb, price (\$/t)	695–776
3. Pb, yield (%)	55–60

- cleaning systems for gas and liquid waste.

Comparing the two methods, the pyrometallurgical method seems more appropriate for the Greek industry, as it offers the following advantages.

- The pyrometallurgical method is a well-tested commercial method.
- The large electric power demand of the hydrometallurgical method, combining with the high price of electric energy in Greece, increases dramatically the operating expense of this method.
- The pyrometallurgical process is a more simplified method compared with the hydrometallurgical method.

A suggested flow diagram of the process is schematically presented in Fig. 4. The quantities of the secondary products of the suggested technology using the pyrometallurgical method are shown in Table 1.

Regarding the separation and recovery of lead, one should mention the following.

- The high value of the processed metals makes a high rate of recovery necessary (> 85%).
- High purity of secondary products must be ensured, in accordance with the market's standards.

5. Economic evaluation and sensitivity analysis

An evaluation of two alternatives was carried out, based on quantitative, economical criteria. The two scenarios are described as follows.

Case 1. Installation of an additional process unit, treating the slurry of Na_2SO_4 and producing crystallized Na_2SO_4 , for commercial use.

Case 2. Installation of an additional process unit producing H_2SO_4 and NaOH for commercial use by electrolysis of Na_2SO_4 .

For each case, a sensitivity analysis was carried out, using the following criteria:

- Internal rate of return (IRR);
- Venture worth (W).

The following three parameters were considered for the sensitivity analysis:

- Capacity of the unit (Q);
- Total lead production (A);

Table 3

Results of the economic analysis ($Q = 17\,000$ t/year, $A = 0.6$, $P = 776\$/t$) [22,23]

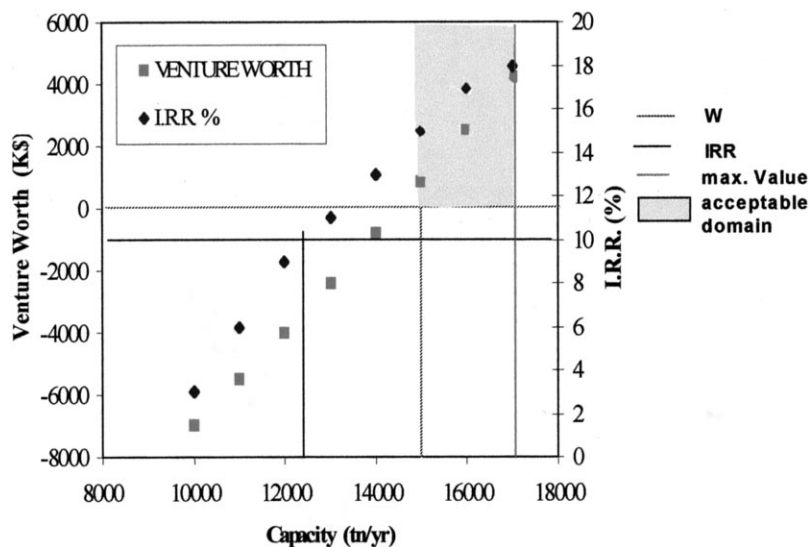
Case 1	Crystallization of Na_2SO_4
Equipment cost	360 (10^3 \$)
Total investment cost	2.5 (10^6 \$)
Total operating cost	4.6 (10^6 \$)
Case 2	Electrolysis of Na_2SO_4
Equipment cost	290 (10^3 \$)
Total investment cost	2.4 (10^6 \$)
Total operating cost	4.3 (10^6 \$)

- The price of secondary produced lead (P);

The limits of the parameters were determined considering the data from the literature and the market survey. The following parameter limits were considered:

- $1000 < Q < 17\,000$ t/year
- $55 < A < 60\%$
- $740 < P < 776\$/t$

The results of the sensitivity analysis are summarized in Table 2. The viability of the process unit of this study, was expressed in terms of $W > 0$ and $\text{IRR} > 10$ (evaluation estimates were carried out regarding US dollars). The sensitivity analysis proved that both processes are economically feasible. Case 2 seems more flexible considering the unit capacity. Considering the maximum capacity of 17 000 t/year, which corresponds to the estimated total annual amount of spent batteries in Greece, the economic analysis gave the results shown on Table 3. Comparing the

Fig. 5. Influence of the plant's capacity on W and IRR ($A = 0.6$, $P = 776\$/t$).

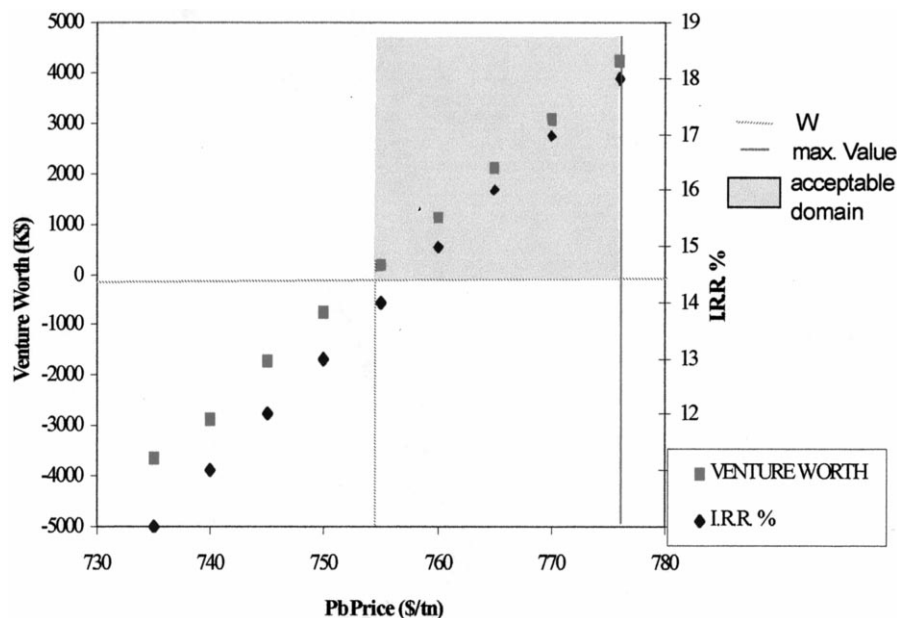


Fig. 6. Influence of lead's price on W and IRR ($Q = 17\,000$ t/year, $A = 0.6$).

two cases, it could be observed that both necessitate higher operating cost than fixed cost investment. In Figs. 5–10, the results of the sensitivity analysis are presented [22].

5.1. Discussion

Although the results derived by this study were based on data concerning Greece, basic conclusions could be exploited in relevant cases of other countries of the Mediterranean Basin, Asia and Africa. A survey carried out for the purposes of this work, revealed that a plethora of universities, research institutes, investors, organizations, companies and other entities participating in Research World Exchange Network (RWEN), are interested in collaborating or asking information inquiring data either for new battery recycling units design or educational practice.

Regarding the sensitivity analysis of case 1, the parameters were considered as mentioned. Fig. 5 presents the relation between W and IRR, as a function of the unit capacity. The analysis proved that the minimum acceptable capacity value for a viable recycling process unit is 15 000 t/year. The estimated spent batteries total amount is predicted to be 17 000 t/year. Considering the results from Fig. 5, it seems that a process unit installed in Greece, having a capacity from 15 000 to 17 000 t/year could be viable. In Fig. 6, the Pb price influence on W and IRR is depicted. The analysis showed that the minimum Pb price should be 755\$/t. This price corresponds to the capacity of 17 000 t/year during the economic life of the

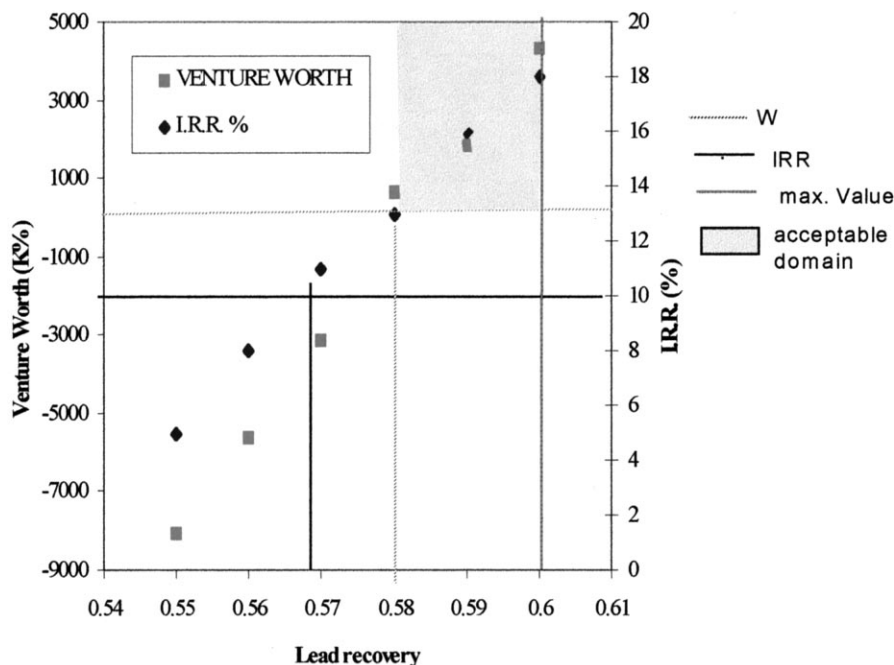


Fig. 7. Influence of maximum lead recovery on W and IRR ($Q = 17\,000$ t/year, $P = 776$ \$/t).

unit. Comparing this value with the estimated market price of lead for the year 2000 (starting year of the unit), which equals 776 \$/t, it is obvious that there is a narrow set of Pb prices that can permit increase of competitiveness of the future unit in Greece. Regarding the Pb desired rate of recovery (Fig. 7), it can be observed that an acceptable rate should be greater than 58%.

Summarizing the results from case 1, the following recommendation for a viable process unit could be expressed:

$$15\,000 < Q < 17\,000 \text{ t/year}$$

$$755 < P < 776 \text{ \$/t}$$

$$A > 0.58$$

The same process was carried out for case 2 from Figs. 8–10. It is obvious that the acceptable values for both criteria are the following:

$$11\,000 < Q < 17\,000 \text{ t/year}$$

$$695 < P < 776 \text{ \$/t}$$

$$A > 0.55$$

6. Conclusions

The disposal of spent lead/acid batteries is an increasing worldwide problem. Additionally, the lack of considerable lead resources and the need for environmen-

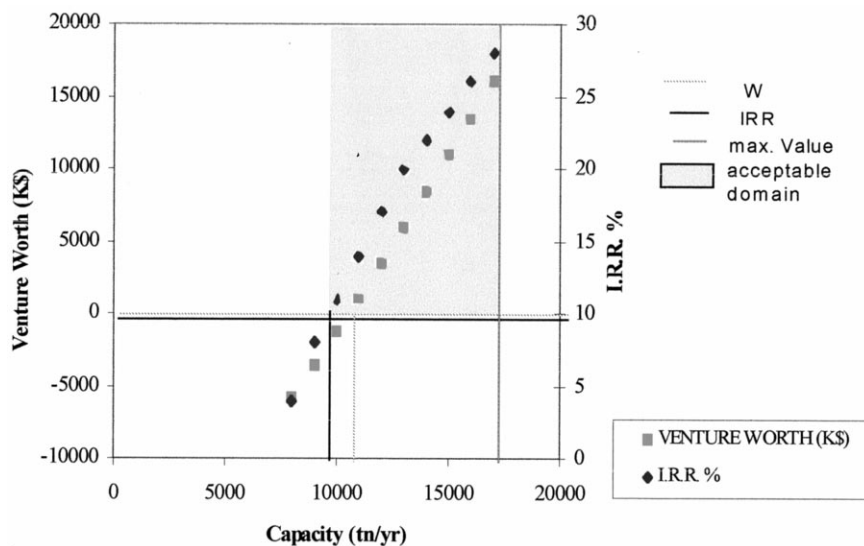


Fig. 8. Influence of plant's capacity on W and IRR ($A = 0.6$, $P = 776\$/t$).

tal protection necessitate spent batteries treatment and lead recovery. The legislation concerning lead/acid batteries is both extensive and complex. European regulation has become more demanding and more strict. Increased focus on environmental issues by government bodies, environment groups and local communities will result in more compliance standards. The EEC regulation requires that EEC states establish separate lead/acid battery collection, disposal and recycling programs. In many European countries, individual actions have been promoting the collection of spent batteries.

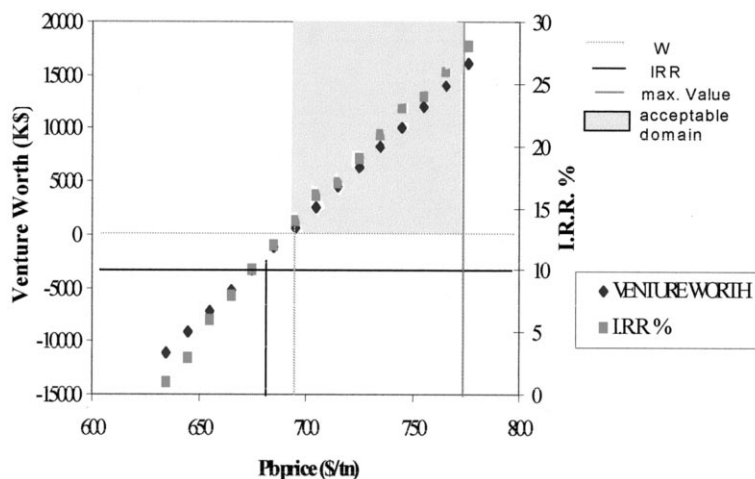


Fig. 9. Influence of lead's price on W and IRR ($Q = 17\,000$ t/year, $A = 0.6$).

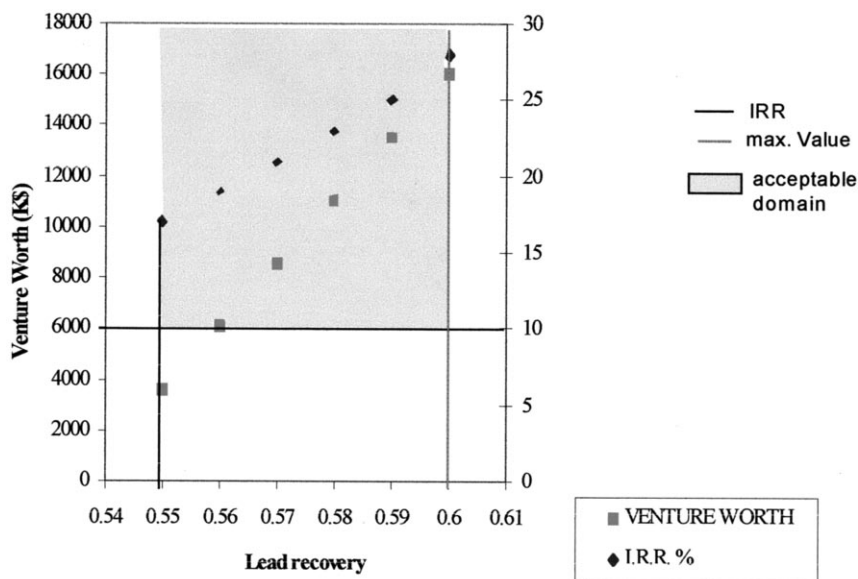


Fig. 10. Influence of maximum lead recovery on W and IRR ($Q = 17\,000$ t/year, $P = 776$ \$/t).

Despite the fact that an organized collection system does not exist in Greece, there are three cases of lead/acid battery recycling sites, where 80% of the annual load of used lead/acid batteries is nowadays handled. This resulted from a market survey and a search we conducted around the Greek territory. The quantity of vehicles is predicted to be 4 000 000 for the year 1998 and 4 200 000 for the year 2000. According to this prediction, the total number of spent batteries in Greece for the year 2000 is estimated to be 1 200 000, which equals 17 000 t/year.

The suggested technology is a widely used commercial process (Brittania Refined Metals, Bodigen, B.J. Industries) and has proved to combine a great variety of advantages. There are two general methods for lead recovery: the 'pyrometallurgical' and the 'hydrometallurgical' process. For a process unit installed in Greece, the pyrometallurgical process seems to combine more advantages (e.g. lower electrical power consumption and operating cost). The present work examines only the pyrometallurgical process. The hydrometallurgical process was not examined in this work; however, it could also be applied for a possible process unit in Greece.

A sensitivity analysis was carried out, using the unit's capacity, the market price of lead and the rate of recovery of lead as significant parameters affecting the viability of the proposed recycling scheme. Sensitivity analysis took under consideration two alternatives of the pyrometallurgical process: The crystallization of Na_2SO_4 was produced as a by-product of the desulfurization reaction (case 1) and electrolysis of Na_2SO_4 (case 2). The results for case 1 indicate that, for a viable unit, the capacity could be between 15 000 and 17 000 t/year, the allowable Pb price between 755 and 776\$/t, and the rate of Pb recovery greater than 0.58. The

corresponding values for case 2 could be: $11\,000 < Q < 17\,000$ t/year, $695 < P < 776$ and $A > 0.55$, respectively.

An economic analysis was carried out regarding a process unit of 17 000 t/year, which is the predicted capacity for Greece for the start-up year (2000). The economic analysis revealed that both cases demand significant operating costs compared with the total investment. Case 2 appears to be more economical. The results from the sensitivity analysis and the economic analysis indicate that a viable solution for spent battery treatment in Greece is to install one plant located in Athens or generally in the Central Greece region, where almost the half the quantity of spent batteries are collected. A recycling scheme applied in Greece must have a form that secures the maximum flow of scrapped batteries to the lead recovering process and to respect environmental protection. This scheme could be a process unit in an existing Greek industry or in a new recycling plant.

However, prior to the installation of a recycling plant, the collection of the scrap batteries must be assured. In Greece, the need for a collection scheme is not still defined. Decisive factors, which will influence the collection of the available scrap batteries in Greece, could be a recycling program, which will create a general consensus on the batteries disposal by the car owners, creation of collection centers and incentives to encourage extensive recycling, and an offered price for the used battery, which can influence the financial viability of the collection scheme.

Although the results derived by this study were based on data concerning Greece, basic conclusions could be exploited in relevant cases of other countries of the Mediterranean Basin, Asia and Africa, with the similar spent lead/acid batteries disposal and collection problems (e.g. uncontrolled refuse of batteries or parts of them, lack of an organized collection system, a plethora of car-service stations, private collectors or mediators between the car owner and the battery disposal sites and the numerous junk yards).

<i>A</i>	Recovery, kg lead/kg battery
IRR	Internal rate of return
<i>P</i>	Price, \$/t
Pb	Lead
<i>Q</i>	Capacity, t/year
t	tonnes
<i>W</i>	Venture worth

References

- [1] Lund HF. The McGraw Hill Recycling Handbook. New York: McGraw-Hill, 1993.
- [2] de Feraudy H. Recycling the plastic components in today's lead/acid battery. *J Power Sources* 1993;42:315–8.
- [3] Jolly R, Rhin C. The recycling of lead batteries: production of lead and polypropylene. *Resour Conserv Recycl* 1994;10:137–43.

- [4] Kassem ME. Feasibility of recycling lead batteries in GCC region. *Metallwissensch Techn* 1992;46/9:917–21.
- [5] Bourson J-L. Recycling of lead/acid batteries in a small plant. *J Power Sources* 1995;57:81–3.
- [6] McColl KG. Regulatory trends in the battery industry. *J Power Sources* 1994;48:29–36.
- [7] Wiaux JP, Waefer JP, Lazouni A, Imbruglia P. Recycling spent batteries. A case study on the association of technologies for metal bearing waste management. *Recov Recycl Reintegration* 1995;1:81–86.
- [8] Amiridis K. ALAKO. Personal Contact. April 1997, Lavrio, Attica.
- [9] Maja M, Bodoardo S, Serracane C, Baurdino R. Dissolution of pastes in lead-acid battery recycling plants. *J Appl Electrochem* 1993;23:819–26.
- [10] Statistical yearbook of Greece for the years 1994–1995 (1996), National Statistical Service, Athens (in Greek).
- [11] Official Newspaper of the Greek Government. No. 73537/1438. 2nd issue, no. 781, 1995.
- [12] Official Newspaper of the Greek Government. No. 19396/1546. 2nd issue, no. 604, 1997.
- [13] Varveris KN. Greece agent for ALAKO batteries. Personal Contact. March 1997, Thessaloniki.
- [14] Mousikos S. Owner of a scrap-metal junk-yard. Personal Contact. March 1997, Thessaloniki.
- [15] Okuda M, Tomisaki K. Process of regenerating and recovering lead sulphate wastes. US Patent 4 222 769, 1980.
- [16] Olper M, Francchia P. Engitec Impianti SpA. Hydrometallurgical process for the overall recovery of the components of exhausted lead-acid batteries. US Patent 4 769 116, 1988.
- [17] Olper M, Francchia P. Engitec Impianti SpA. Hydrometallurgical process for recovery in pure metal form all the lead contained in the active mass of exhausted batteries. US Patent 4 927 510, 1990.
- [18] Prengaman RD, McDonald HB. RSR Corporation. Method of recovering lead values from battery sludge. US Patent 4 229 271, 1980.
- [19] Buren KJA, Hedlund ML, Lundstrom MS. Boliden Aktiebolag. A method of recovering lead from waste lead products. European Patent Application 0 132 243, 1985.
- [20] Sabin Cullen, Global Aenecology Corporation. Battery paste recycling process. WO 97/12998, 1997.
- [21] CX System Plant. For the environmental clean treatment of spent lead acid batteries and the recovery of battery components. Advertising Brochure of Engitec Impianti S.p.A. Italy, 1995.
- [22] Kouskoumvekaki E. Feasibility study of lead/acid batteries recycling. Diploma Thesis. Chemical Engineering Department, Aristotle University of Thessaloniki, 1998 (in Greek).
- [23] Hall DJL. Monometer Furnaces. Personal contact, October 1997, Essex, UK.